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Timing an Accreting Millisecond Pulsar: Measuring the Accretion Torque in IGR J00291+5934

L. Burderi[1 ⋆], T. Di Salvo[2], A. Riggio[2], M.T. Menna[3], G. Lavagetto[2], A. Papitto[3], R. Iaria[2], N. R. Robba[2] and L. Stella[3]

[1] Università degli Studi di Cagliari, Dipartimento di Fisica, SP Monserrato-Sestu, KM 0.7, 09042 Monserrato, Italy

[2] Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, via Archirafi 36 - 90123 Palermo, Italy

[3] I.N.A.F. - Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monteporzio Catone (Roma), Italy

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Abstract We present here a timing analysis of the fastest accreting millisecond pulsar IGR J00291+5934 using RXTE data taken during the outburst of December 2004. We corrected the arrival times of all the events for the orbital (Doppler) effects and performed a timing analysis of the resulting phase delays. In this way we find a clear parabolic trend of the pulse phase delays showing that the pulsar is spinning up as a consequence of accretion torques during the X-ray outburst. The accretion torque gives us for the first time an independent estimate of the mass accretion rate onto the neutron star, which can be compared with the observed X-ray luminosity. We also report a revised value of the spin period of the pulsar.

Key words: accretion, accretion disks — stars: neutron — stars: magnetic fields — pulsars: general — pulsars: individual: IGR J00291+5934 — X-ray: binaries

1 INTRODUCTION

The so-called recycling scenario links two different classes of astronomical objects, namely the millisecond radio pulsars (usually found in binary systems) and the Low Mass X-ray

⋆ E-mail: `burderi@mporzio.astro.it`

Binaries (hereafter LMXBs), or, at least, a subgroup of them. The leading idea of this scenario is the recycling process itself, during which an old, weakly magnetized, slowly spinning neutron star is accelerated by the accretion of matter and angular momentum from a (Keplerian) accretion disk down to spin periods in the millisecond range. In this way, at the end of the accretion phase, the neutron star rotates so fast that it is resurrected from the radio pulsar graveyard, allowing the radio pulsar phenomenon to occur again despite the weakness of the magnetic field.

Although this scenario was firstly proposed long time ago (see e.g. Bhattacharya & van den Heuvel 1991 for a review), the most embarassing problem was the absence of coherent pulsations in LMXBs. Only recently, the long seeked for millisecond coherent oscillations in LMXBs have been found, thanks to the capabilities (the right combination of high temporal resolution and large collecting area) of the RXTE satellite. In April 1998, a transient LMXB, SAX J1808.4–3658, was discovered to harbour a millisecond pulsar ($P_{\rm spin} \simeq 2.5$ ms) in a compact ($P_{\rm orb} \simeq 2$ h) binary system (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). We now know seven accreting millisecond pulsars (Wijnands 2005; Morgan et al. 2005); all of them are X-ray transients in very compact systems (orbital period between 40 min and 4 h), the fastest of which ($P_{\rm spin} \simeq 1.7$ ms), IGR J00291+5934, has been discovered in December 2004 (Galloway et al. 2005, hereafter G05). Timing techniques applied to data of various accreting millisecond pulsars, spanning the first few days of their outbursts, allowed an accurate determination of their main orbital parameters. However, only a few attemps have been made to determine the spin period derivative (Chakrabarty et al. 2003; Galloway et al. 2002).

In this paper we apply an accurate timing technique to the fastest currently known accreting millisecond pulsar, IGR J00291+5934, in the hope of constraining the predictions of different torque models with good quality experimental data. Our results indicate quite clearly that a net spin up occurs during the December 2004 outburst of IGR J00291+5934 (see also Falanga et al. 2005) and that the derived torque is in good agreement with that expected from matter accreting from a Keplerian disk.

2 THE TIMING TECHNIQUE

In standard timing techniques (see e.g. Blandford & Teukolsky 1976) the predicted arrival time of a given pulse is computed using a first guess of the parameters of the system, and the difference between the experimental and predicted arrival times, namely the residuals, are fitted with a linear multiple regression of the differential corrections to the parameters. This means that the differential correction to orbital parameters, source position in the sky, spin frequency and its derivative, are computed simultaneously. This technique has the obvious advantage to give a self-consistent solution, where all the correlations in the covariance matrix of the system are fully taken into account. However, the convergency of

the fit is not always guaranteed and – especially on long temporal baselines – convergence to secondary minima could occur.

On the other hand, if the orbital period is much shorter than the timescale on which the spin period derivative is expected to produce a significant effect, we can demonstrate that a different timing technique is more effective in determining the spin period derivative. This technique relies on the fact that the delays in the arrival times produced by the orbital corrections are effectively decoupled from those caused by the spin evolution. The technique proceedes as follows: in order to obtain the emission times, $t_{\rm em}$, the arrival times of all the events, $t_{\rm arr}$, are firstly reported to the Solar system barycenter adopting the best estimate of the source position in the sky, then corrected for the delays caused by the binary motion using the best estimate of the orbital parameters through the formula:

$$t_{\rm em} \simeq t_{\rm arr} - x \sin\left[\frac{2\pi}{P_{\rm orb}}\left(t_{\rm arr} - T^*\right)\right], \tag{1}$$

where $x = a \sin i/c$ is the projected semimajor axis in light seconds, and T^* is the time of ascending node passage at the begining of the observation. In the following, for simplicity, we use t instead of $t_{\rm em}$. The differential of this expression with respect to the orbital parameters allows to calculate the uncertainties in the phases, $\sigma_{\phi\,{\rm orb}}$, caused by the uncertainties in the estimates of the orbital parameters. In a similar way, we have computed the uncertainties in the phase delays, $\sigma_{\phi\,{\rm pos}}$, caused by the uncertainties on the estimates of the source position in the sky. In this case we can estimate $\dot{\nu}$ fitting the measured phase variations, while the uncertainties in the adopted orbital parameters and source position will result in a "timing noise" of amplitude $\sigma_{\phi\,{\rm par}} = (\sigma^2_{\phi\,{\rm orb}} + \sigma^2_{\phi\,{\rm pos}})^{1/2}$ (see Burderi et al. 2005 for details).

3 OBSERVATIONS AND DATA ANALYSIS

IGR J00291+5934 was observed by RXTE between 2004 December 3 and 21. In this paper we report on the data between December 7 and 21 taken from a public ToO. We mainly use data from the PCA for timing anaysis and data from PCA and HEXTE for spectral analysis. The arrival times of all the events were converted to barycentric dynamical times at the solar system barycenter. The position adopted for the source was that of the proposed radio counterpart (which is compatible with that of the proposed optical counterpart, see Rupen et al. 2004). We corrected the arrival times of all the events for the delays caused by the binary motion using eq. (1) with the orbital parameters given in G05.

Adopting the uncertainties in the estimates of the orbital parameters given in G05, the positional uncertainty of $0.04''$ radius reported by Rupen et al. (2004) we obtain: $\sigma_{\phi\,{\rm orb}} \lesssim 0.01$, $\sigma_{\phi\,{\rm pos}} \lesssim 0.006$ where we have maximized sin and cos functions with 1, and used $t - T_0 \lesssim 7$ days. Therefore, we expect that the uncertainties in the orbital parameters and source position will cause a "timing noise" not greater than $\sigma_{\phi\,{\rm par}} \times P_{\rm spin} \sim 0.02$ ms.

To compute phases of good statistical significance we epoch folded each interval of data in which the pulsation was significantly detected at the spin period given in G05 with respect to the same reference epoch, T_0, corresponding to the begining of our observations. The fractional part of the phase was obtained fitting each pulse profile with a sinusoid of fixed period. To compute the associated errors we combined the statistical errors derived from the fit, $\sigma_{\phi\,\mathrm{stat}}$, with the errors $\sigma_{\phi\,\mathrm{par}}$.

In order to derive the differential correction to the spin frequency, $\Delta\nu_0$, and its derivative, $\dot{\nu}_0$, at the time T_0 we have to derive a functional form for the time dependence of the phase delays. We started from the following simple assumptions: i) the bolometric luminosity L is a good tracer of the mass accretion rate $\dot{M}$ *via* the relation $L = \zeta(GM/R)\dot{M}$, where $\zeta \leq 1$, and G, M, and R are the gravitational constant and the neutron star mass and radius, respectively. ii) The matter accretes through a Keplerian disk truncated at the magnetospheric radius, $R_{\mathrm{m}} \propto \dot{M}^{-\alpha}$, by its interaction with the (dipolar) magnetic field of the neutron star. At R_{m} the matter is forced to corotate with the magnetic field of the neutron star and is funneled (at least in part) towards the rotating magnetic poles, thus causing the pulsed emission. For standard disk accretion $\alpha = 2/7$. Indeed we considered two extreme cases, namely $\alpha = 2/7$ and $\alpha = 0$, since a location of R_{m} independent of $\dot{M}$ has been proposed (see, *e.g.*, Rappaport, Fregeau, and Spruit, 2004). iii) The matter accretes onto the neutron star its specific Keplerian angular momentum at R_{m}, $\ell = (GMR_{\mathrm{m}})^{1/2}$, thus causing a material torque $\tau_{\dot{M}} = \ell \times \dot{M}$. A firm upper limit to this torque is given by the condition $\tau_{\dot{M}} \leq \ell_{\max} \times \dot{M}$, with $\ell_{\max} = (GMR_{\mathrm{CO}})^{1/2}$, where $R_{\mathrm{CO}} = 1.50 \times 10^8\ m^{1/3}\nu^{-2/3}$ is the corotation radius (namely the radius at which the Keplerian frequency equals the spin frequency ν of the neutron star and beyond which accretion is centrifugally inhibited), and $m = M/\mathrm{M}_{\odot}$. We *do not consider* any form of threading of the accretion disk by the magnetic field of the neutron star (see e.g. Rappaport, Fregeau, and Spruit 2004 for a description of the magnetic threading), which implies that the only torque acting during accretion is $\tau_{\dot{M}}$.

In these hypothesis the spin frequency derivative is $\dot{\nu} = \ell\,\dot{M}/(2\pi I)$, where I is the moment of inertia of the neutron star and we have neglected any variation of I caused by accretion. If $\dot{M} = \dot{M}(t)$, we have $\dot{\nu}(t) = (2\pi I)^{-1}\ell_0\dot{M}_0(\dot{M}(t)/\dot{M}_0)^{1-\alpha/2}$, where $\ell_0 = (GMR_{\mathrm{m}\,0})^{1/2}$, and $R_{\mathrm{m}\,0}$ and $\dot{M}_0$ are R_{m} and $\dot{M}$ at $t = T_0$, respectively. For the $\alpha = 0$ case we assumed $\ell_0 = \ell_{\max}$.

Since we assumed $\dot{M}(t) \propto L(t)$, to determine the temporal dependence of $\dot{M}(t)$ we studied the energy spectra of the source for each continuous interval of data combining PCA and HEXTE data. All the spectra are well fitted with a model consisting of a power law with an exponential cutoff plus thermal emission from a Keplerian accretion disk modified by photoelectric absorption and a Gaussian iron line. In order to derive $L(t)$ for each spectrum we made the simple assumption $L(t) \propto F_{(3-150)}(t)$, which is the unabsorbed flux in the RXTE PCA plus HEXTE energy band ($3-150$ keV). A good fit of

Table 1 Orbital and spin parameters of IGR J00291+5934.

Parameter	G05	This work
Projected semimajor axis, $a_1 \sin i$ (lt-ms)	64.993(2)	–
Orbital period, $P_{\rm orb}$ (s)	8844.092(6)	–
Epoch of ascending node passage, T^* (MJD)	53345.1619258(4)	–
Eccentricity, e	$< 2 \times 10^{-4}$ (3 σ)	–
Spin frequency, ν_0 (Hz)	598.89213064(1)	598.89213053(2)
Spin frequency derivative, $\dot{\nu}_0$ (Hz/s)	$< 8 \times 10^{-13}$ (3 σ)	–
Spin frequency derivative, $\dot{\nu}_0$ (Hz/s) ($\alpha = 0$)	–	$1.17(0.16) \times 10^{-12}$
Spin frequency derivative, $\dot{\nu}_0$ (Hz/s) ($\alpha = 2/7$)	–	$1.11(0.16) \times 10^{-12}$
Spin frequency derivative, $\dot{\nu}_0$ (Hz/s) ($\dot{\nu}$ = constant)	–	$0.85(0.11) \times 10^{-12}$
Epoch of the spin period, T_0 (MJD)	–	53346.184635

Errors are given at 1σ confidence level.

$F_{(3-150)}(t)$ *vs* t between December 7 and 14 ($\Delta t_{\rm obs} \sim 7.3$ days) is given by the expression $F_{(3-150)}(t) = F_{(3-150)} \times [1 - (t - T_0)/t_B]$ with $t_B = 8.4 \pm 0.1$ days, where $F_{(3-150)}$ is the unabsorbed flux at $t = T_0$. Therefore we have $\dot{\nu}(t) = \dot{\nu}_0 \times [1 - (t - T_0)/t_B]^{1-\alpha/2}$, where the spin frequency derivative at $t = T_0$ is $\dot{\nu}_0 = (2\pi\, I)^{-1}\, \ell_0\, \dot{M}_0$. We have therefore fitted the phase delays with the function:

$$\phi = -\phi_0 - \Delta\nu_0\,(t - T_0) - \frac{1}{2}\dot{\nu}_0 (t - T_0)^2 \times \left[1 - \left(\frac{2-\alpha}{6}\right) \times \frac{(t - T_0)}{t_B}\right]. \qquad (2)$$

Using the best fit value for $\Delta\nu_0$ we computed the improved spin frequency estimate and repeated the same procedure described at the begining of this paragraph, folding at the new estimate of the spin period. The new phases were fitted with eq. (2). In this case, $\Delta\nu_0$ was fully compatible with zero. These phases are plotted versus time in Figure 1 (upper panel) together with the residuals in units of σ with respect to eq. (2) (lower panel). The best fit estimates of ν_0 and $\dot{\nu}_0$ are reported in Table 1 for three values of α, namely $\alpha = 0$ which correspond to a location of $R_{\rm m}$ independent of the accretion rate (cfr. the model of Rappaport Fregeau, and Spruit 2004 in which $R_{\rm m} = R_{\rm CO}$ for any $\dot{M}$), the standard case $\alpha = 2/7$ which corresponds to $R_{\rm m}$ proportional to the Alfvén radius, and $\alpha = 2$ which has been given for comparison purposes and corresponds to a parabolic trend, expected in the case of constant $\dot{M}$. The statistics is not good enough to distinguish between these three possibilities.

From the best-fit value of the spin frequency derivative $\dot{\nu}_0$ we can compute the mass accretion rate at $t = T_0$ through the formula: $\dot{M}_{-10} = 5.9 \times \dot{\nu}_{-13}\, I_{45}\, m^{-2/3} (R_{\rm CO}/R_{\rm m\,0})^{1/2}$, where $\dot{M}_{-10}$ is $\dot{M}_0$ in units of $10^{-10}\, M_\odot$ yr^{-1}, $\dot{\nu}_{-13}$ is $\dot{\nu}_0$ in units of 10^{-13} s^{-2}, and I_{45}

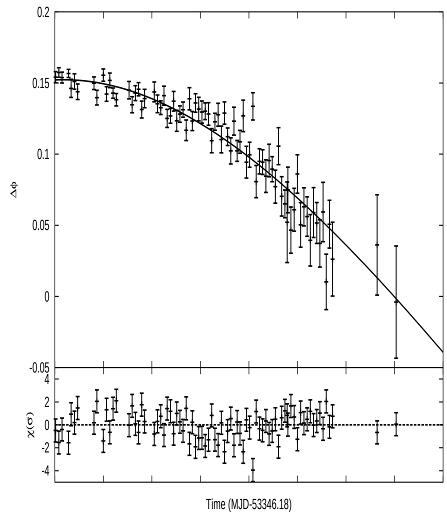

Fig. 1 Pulse phases computed folding at the spin period reported in Table 1 and plotted versus time together with the best fit curve for $\alpha = 2/7$ shown as a solid line (upper panel) and residuals in units of σ (lower panel). Note that the linear term is fully compatible with zero.

is I in units of 10^{45} g cm^2. In the following we will adopt the FPS equation of state for the neutron star matter for $m = 1.4$ and the spin frequency of IGR J00291+5934 which gives $I_{45} = 1.29$ and $R = 1.14 \times 10^6$ cm (see e.g. Cook, Shapiro & Teukolsky 1994). In order to compare the experimental estimate of $\dot{M}_0$ with the observed X-ray luminosity, we have to derive the bolometric luminosity $L(t)$ from the observed flux $F_{(3-150)}(t)$. To this end we consider the spectral shape at $t = T_0$ in more detail.

The power law is the dominant spectral component. This component presumably originates in an atmosphere of small optical depth just above each polar cap (see e.g. Poutanen & Gierlinski 2003; Gierlinski & Poutanen 2005), thus we neglect, to first order, any effect of the inclination of the emitting region with respect to the observer. On the other hand, we observe a single-peaked pulse profile, which means that we only see the emission from one of the polar caps (e.g. Kulkarni & Romanova 2005). We have therefore multiplied by 2 the unabsorbed flux of the power law in order to take into account the emission of the unseen polar cap. Assuming isotropic emission, we computed $L_{\rm PL} \simeq 2F_{\rm PL\,(0,\infty)} \times 4\pi d^2 = 1.5^{+0.4}_{-0.3} \times 10^{37}\ d^2_{5\,\rm kpc}$ erg/s, where $d_{5\,\rm kpc}$ is the source distance in units of 5 kpc. The uncertainty on the luminosity has been evaluated propagating the uncertainties on the spectral parameters threated as they were independent on each other.

The second component is the thermal emission from a Shakura-Sunyaev accretion disk. The fraction of the total luminosity that is emitted by the disc is given by the ratio:

$0.5R/R_{\mathrm{m}\,0} = 0.34$. In this hypothesis $L_{\mathrm{BB}\,0} = 0.39/(1-0.39) \times L_{\mathrm{PL}\,0} = 9.6 \times 10^{36}\, d^2_{5\,\mathrm{kpc}}$ erg/s. The total bolometric luminosity is therefore $L_0 = 2.46^{+0.94}_{-0.29} \times 10^{37}\, d^2_{5\,\mathrm{kpc}}$ erg/s. If we compare this luminosity with the mass accretion rate inferred from the timing analysis, we obtain an estimate of the source distance, which is: $d = 9.47^{+1.2}_{-2.1}$ kpc.

4 CONCLUSIONS

We have analysed RXTE data of the fastest known accreting millisecond pulsar, IGR J00291+5934, during the period $7-14$ December, 2004. We report a revised estimate of the spin period and the spin period derivative. The source shows a strong spin-up, which indicates a mass accretion rate of about $8.5 \times 10^{-9}\, M_\odot$ yr^{-1}. Comparing the bolometric luminosity of the source as derived from the X-ray spectrum with the mass accretion rate of the source as derived from the timing, we find a good agreement if we place the source at a quite large distance between 7 and 10 kpc. Note that 10 kpc is close to the outer edge of our Galaxy in the direction of IGR J00291+5934. Another possibility is that part of the luminosity of the system is not observed because emitted in other energy bands or because of occultation effects (which may be favoured if indeed the source is highly inclined).

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